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MEASURING SLEEP BY WRIST ACTIGRAPH

ANNUAL REPORT

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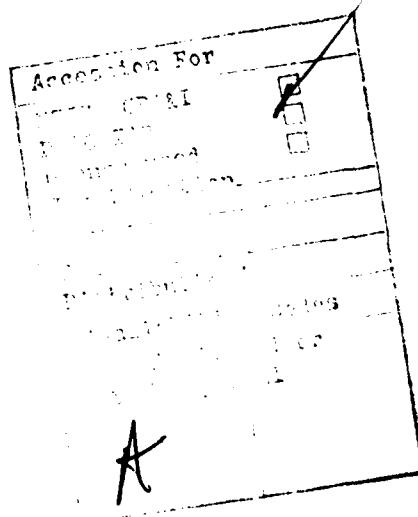
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20. Abstract, continued.

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ABSTRACT

Using a piezo-electric transducer, wrist activity was recorded
simultaneously with EEG, EOG, and EMG to obtain 102 recordings —
39 from hospital patients and 63 from non-patients — during both
Sleep and Wakefulness. On a minute-to-minute basis, wrist activity
alone was used to estimate Sleep Time. Blind independent scoring
of the EEG-EOG-EMG records was also done for Sleep and Wakefulness.
Results from the two Sleep/Wake estimations agreed 94.5% of the
minutes. Correlations between the two methods were determined for
Total Sleep Period (r=0.90), Total Sleep Time (r=0.89), Total Wake
Within Sleep (r=0.70), and number of Mid-Sleep Awakenings (r=0.25).
Correlation coefficients were even higher when the 39 patients were
excluded from the computations. On the average, the actigraphic
method overestimated Sleep Time by 10 minutes. Continuous wrist
activity recordings provide simple, inexpensive, but very accurate
estimates of Sleep Time.

FORWORD

For the protection of human subjects the investigator has adhered to
policies of applicable Federal Law 45CFR46.

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INTRODUCTION

Sleep loss and combat fatique are increasing concerns to the modern army for several reasons. First, lapses of attention may be far more serious for the soldier who operates smart weapons, vehicles, radios, monitors radar, etc. than they were for the traditional infantryman who carried a pack and dug forholes. Second, any future general war is likely to be extremely brief and intense, with victory and defeat determined in a few days or weeks. Soldiers in a future war using technically sophisticated modern weaponry will have little time for sleep, and plans must be made to enable personnel to perform effectively throughout the duration of a combat of unprecedented intensity. Finally, American troops may have to enter combat immediately after airlift from remote parts of the world, and plans must be developed to minimize the effects of jet lag on personnel performance.

In order to assess the effects of sleep loss, sleep schedule changes, jet lag, etc. upon operational performance of troops in actual field conditions, a practical method of quantifying sleep is needed which is cost-effective and reliable. Traditional methods of physiologic monitoring of sleep through EEG-EOG-EMG recordings are completely impractical for actual or simulated combat settings, yet it has also been shown that subjective monitoring of subjects is unreliable (Carskadon, et al, 1976). In addition, both electroencephalographic measures and observational methods for measuring sleep are costly, and considerable time is necessary in order to quantify sleep time by scoring EEG records.

Employing Delgado's (1963) telemetric activity recording device, Kupfer et al (1972) and Foster et al (1972a,1972b) have described the use of a telemetric system for quantifying sleep and assessing sleep quality in humans. Encouraged by the high correlations between EEG and actigraphic estimates of sleep--0.84 and 0.88 in two separate studies (Kupfer et al, 1972; Kupfer and Foster, 1973)--Kripke et al (1977) developed a more flexible system for distinguishing sleep and wakefulness using wrist activity. Initial pilot results validated the usefulness of our analog recording device for this purpose. With five subjects, Kripke et al (1978) obtained a 0.98 correlation between sleep duration determined from wrist activity and the EEG. In our 1978-1979 contract, we have further

demonstrated the reliability of analog wrist actigraphic recordings for
quantifying sleep with a much larger (N=102) number of recordings from a
more diverse group of subjects including hospital patients with varying
degrees and types of insomnia.

METHOD

Subjects   Approximately 130 subjects were employed.   Subjects included
both males and females ranging in age from 17 to 66 ($\bar{X}$ age=33.6, sd=13.5).
Thirty-nine of these were hospitalized patients from three wards who were
chosen to test the effectiveness of the scoring in subjects with very
disturbed sleep.   These patients were suffering from psychiatric problems,
alcoholism, or chronic pain, and, in addition to other complaints, almost
all of them suffered some degree of insomnia.   The sample of 63 non-
patients in our subject population was very heterogeneous and included
college students and hospital staff in good health and who were generally
good sleepers.

Instruments and Procedure   The activity transducer was constructed by
soldering a small steel nut off-center onto a 5-mm length of spring-like
polygraph pen cleaning wire, and clamping the other end of the wire against
a piezo-ceramic element (Kripke et al, 1978).   Because the weight of the
nut is off-center, the piezo-ceramic element is excited when the transducer
is moved in any direction, although the voltage is not linearly related to
motion or acceleration.   The transducer is packaged in a small acrylic box
mounted on a watch band.   A small portable tape recorder, worn on a belt
around the waist, recorded the transducer output.

In order to cross-validate the use of activity recordings for estimating
sleep, parietal-occipital EEG, submental electromyogram (EMG), and electro-
occulogram (EOG) were simultaneously recorded with wrist activity.   A
special pre-amplifier was designed and built in order to amplify EEG and
EMG so that these signals could be recorded with the other data onto a
C-120 cassette.   Thus, four channels of information are recorded on one
cassette.   A digital watch was also employed to superimpose one minute and
ten minute timing marks on the EMG channel throughout the recording in order
to verify the timing of the recording.   A signal mark for the time of going

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to bed was likewise recorded.

Electrodes were attached to the subjects and the activity transducer was mounted on the wrist late in the afternoon. Figure 1 schematically illustrates the placement of the electrodes and the actigraph. The wire from the actigraph was run up the sleeve, over the shoulder and down the back where it was plugged into the recorder. Similarly, the wires from the head and chin electrodes were bundled at the back of the neck and thence were run down the back to the recorder at the waist.

After being equipped for the physiological recordings and instructed to press the button of the signal marker to indicate bedtime, subjects left the lab. They were instructed to go about their normal routines with the exception of any activities which could jeopardize the equipment or the recording. Subjects were also asked to fill out a Sleep Log the following morning in order to subjectively estimate sleep time and sleep quality (see Figure 2). They slept at home or in their hospital beds (if they were inpatients) returning to the lab at a convenient time the following morning.

The signals recorded onto the cassette were played back at 60 times the recording speed and dubbed onto an instrumentation tape recorder along with a time code identifying each recorded minute. A segment of the total 16-18 hr recording was selected for analysis. This segment included both Sleep and Wake time. The entire sleep period was surrounded by a deliberately pseudorandomized amount of Wake time. The amount of Wake time which surrounded the sleep period was varied for each subject between 1 and 5.5 hours in order to avoid cueing the scorers. The EEG-EOG-EMG signals from this segment plus the time code were replayed and written onto paper using a polygraph to obtain a standard 15mm/sec recording. Independently, the analog activity recording for the same segment was replayed with the same time code onto a separate chart at 32 mm/min.

The EEG-EOG-EMG recordings were scored according to the criteria of Rechtschaffen and Kales (1968) in one minute epochs, as defined by the time code. Only two scoring categories were derived: Wake (which included both Wake and Movement Time) or Sleep (Stages 1, 2, 3, 4, and REM). Each minute of the actigraphic record was also scored for Wake and Sleep using the best guess which could be derived from activity. If greater than 50% of a one minute epoch contained activity, the epoch was always scored as

Wake. The context of the epoch was also considered so that an epoch with less than 50% activity was scored Wake if it was surrounded by other epochs with sufficient activity.

Figure 3 shows actual excerpts from an actigraph recording of one subject with scoring marks above each trace. The time code is not shown. In these excerpts, the first three 18-minute segments are sequential and are taken from a segment of the record which immediately preceeded sleep. The second tracing shows that activity is tapering off as the subject is quieting down in preparation for sleep. The third tracing shows a cessation of actigraphic signals after eight minutes. At this point, the subject was judged to be asleep. The fourth tracing at the center of Figure 3 is an excerpt from the middle of the sleep period, showing the typically inactive pattern of sleep. Tracing number five begins another sequential series of three 18-minute segments at the end of this subject's sleep period. It contains one minute of activity where the subject was scored as being awake for one minute only. Finally, in the center of tracing number six, the subject awoke and we saw once again an abundance of wrist activity indicating wakefulness.

The EEG-EOG-EMG records were scored by one investigator, a highly experienced scorer of sleep records, while actigraph tracings were scored independently by a second investigator. The activity scorer had not met the subjects and had no knowledge of their subjective Sleep Logs, whereas the EEG scorer had direct contact with the subjects and collected their Sleep Logs thereby acquiring access to additional subjective estimates of sleep time and quality.

After about 60% of the records had been scored, it was realized that the technical quality of recordings (e.g., freedom from artifacts such as 60 Hz interference) and the interpretability of recordings would affect inter-rater agreement. Therefore, the later records were also rated as technically "high" or "low" in quality and their interpretability was likewise rated as high or low, most of the difficult-to-interpret records being obtained from patients with sleep disorders. This prospective scoring (before agreement was determined) was used to evaluate how well scoring unreliability could be recognized.

The separate reliability of EEG and actigraph scoring was checked since these within-method reliabilities limit the cross-correlation

between methods. Ten actigraph records and their corresponding EEG
records were scored by the two raters. Seven of these 10 records
were from patients. All 10 of the EEG records were rated as high quality
but only 8 of the actigraph records were rated high quality. Two EEG
records and 5 of the actigraph records were low on interpretability.

RESULTS

Of the 150 recordings which were made, 102 were of useable quality.
Unuseable records resulted from such problems as electrodes drying,
battery failures, or mechanically defective cassettes, not failure of the
actigraph transducer. We obtained 2 useable recordings from 16 of our
subjects and 3 useable recordings from one subject.

For each recording, the number of minutes for which the actigraph
scorer and the EEG scorer agreed in assigning a designation of Wake or
Sleep was determined as well as the number of minutes where the two
scorers disagreed. For all subjects, the two scorers agreed on 94.5%
of all minutes. The percent agreement for the 63 non-patients was 96.3%.

A more meaningful measure than percent agreement for evaluating
the usefulness of the wrist actigraph for quantifying sleep is the extent
to which the wrist actigraphic scoring reflects inter-subject variability
in sleep time. That is, can we differentiate short sleepers, insomniacs,
etc. using this method? The correlation coefficient between the two
estimates for Total Sleep Time (TST) was $r=0.90$ ($p<.0001$) indicating
that, indeed, the wrist actigraphic scoring did reflect most of the true
variance in sleep time. As is shown in Table 1, the correlation coeffi-
cients between the two methods for estimating our other sleep parameters--
Total Sleep Period (TSP), i.e., the span of time from first to last sleep,
Total minutes of Wake Within Sleep (TWWS), and the number of Mid-Sleep
Awakenings (MSA) were also highly significant.

Although the minute-to-minute agreement and correlations were very
high, we found that the actigraphic scorer's estimate of TST was, on the
average, about 10 minutes greater per night than the EEG estimate, and
this difference was highly significant ($t=3.82$, $p<.001$). Clearly, if a
subject is awake but not moving, he can be erroneously scored asleep,
and this accounts for the difference in the two scoring estimates.

Since the reliability of the actigraphic scoring of sleep, like any

method, will depend on the circumstances wherein it is employed, we thought it useful to explore the relative reliability of the method in different subject groups. Therefore, our sample of 102 subjects was split into 6 binary categories, for example, patients vs non-patients or subjects older than 50 vs subjects younger than 50. Each of these factors we predicted would influence our results: 1) Patienthood--Patients in the study generally had disturbed sleep, were medicated, and, as a consequence, the scorers found their records more difficult to score. 2) Age--Both the EEG scorer and the actigraph scorer had the impression that records obtained from older subjects were more difficult to score so we reasoned that results would be better for subjects younger than 50. 3) Insomnia-- Since insomniacs also produce more difficult-to-score records, subjects with subjective (Sleep Log) estimates of sleep time less than 390 minutes were predicted to produce poorer results than those with longer objective sleep periods or subjective sleep times. 4) Quality and Interpretability-- Records rated by the scorers to be high quality and high in interpretability were predicted to yield better results than records which were somewhat lower on these two factors.

An r to Z transformation was done so that a parametric test described by Hays (1973) could be used to determine if the correlation coefficients in each binary category were significantly different. The results of this significance test were checked in a few cases with a Chi-square test and results were identical. The results of the significance tests are given in Table 2.

In the case of patients and non-patients, significant differences were obtained for all four sleep parameters at the .05 level (one-tailed) and the differences were significant at the .001 level for TSP, TST, and TWWS. We suspect that these differences resulted because the patient group had more disturbed sleep and that, consequently, both EEG and- actigraphic records were more difficult to score. The EEG estimate of the mean total minutes of Wake Within Sleep was 53.2 for patients and only 17.8 for non-patients confirming our suspicion that patients had more disturbed sleep.

As can be seen in Table 2, the differences between binary categories were also highly significant for TST and TSP in the case of age, Sleep Log TST, and quality and interpretation case, but there was no significant difference between subjects whose EEG TSP was < 390 min vs ≥ 390 min. For

Thus there were no significant differences and for MSA only the factors of quality and interpretation contained significant differences in r values for the categories of "high" and "low."

In general, it is apparent that the actigraphic method is extremely accurate for normal subjects who are under 50 years of age and who have no sleep disorders, which would usually be the case with Army troops. Accuracy is lost if the record is technically poor or overtly difficult to interpret, but since these problems can be prospecitvely recognized, they may generally be solved by repeating the unsatisfactory recordings.

In order to assess the reliability of our scoring, the last 10 recordings (described earlier) of both EEG-EOG-EMG and wrist activity were scored independently by both raters. The actigraph records were scored first, then the EEG records. Reliability correlations were computed for the 2 scorings of the EEG records, for the 2 scorings of the actigraph records, and for EEG and activity records. The results of these reliability estimations are shown in Table 3. The inter-rater reliability correlations for estimating all sleep parameters were extremely high for both types of records and, as it happened, the EEG-actigraph correlations were higher for these 10 records than for the whole group of 102 subjects. Table 3 also shows the correlations between methods for estimating sleep parameters for these 10 subjects. Almost all of the correlations are high and, for TST and TWWS, the actigraph-EEG correlations are almost as good as inter-rater EEG correlations. These correlations were actually slightly higher than for the total group of 102 subjects for the estimation of the #MSA which were not significantly correlated. Since #MSA was not significantly correlated for our patient group (see Table 2) and since 7 out of 10 of the subjects in this reliability sample were, in fact, patients, it is possible that the non-significant correlation resulted because these patients had sleep disturbances and were relatively difficult to score. Apparently, when attempting to estimate #MSA, EEG and actigraphic estimates do not agree well when the subjects are patients on medications with disturbed sleep.

Although both agreement between and within methods for estimating sleep time were very high, some attention was given to delineating sources of descrepancy in judging Sleep/Wake. Since the actigraph tended to overestimate TST by a mean of 10 min across all subjects, we counted the number of times the actigraph vs the EEG rater scored sleep onset first.

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Out of 102 records, the actigraphic scorer scored sleep onset first in 54 instances while the EEG scorer scored sleep onset first in 34 cases. In the remaining 14 sleep records, the two raters agreed to the minute when sleep onset occured. Thus, there was a slight tendency for the actigraphic scorer to score sleep onset before the EEG scorer.

Correlation coefficients were also computed between Sleep Log TST and our other two TST estimates in order to determine how well the actigraphic and EEG estimations of sleep compared to subjective estimations. The correlation of EEG and Sleep Log TSTs was $r=.83$ ($p < .0001$) while the correlation of actigraph and Sleep Log TSTs was somewhat lower ($r=.75$, $p < .0001$). As reported earlier, the correlation between the two objective methods of estimating sleep was $r=.90$ ($p < .0001$).

In order to provide a visual comparison which would aid in further examining sources of discrepancies between methods for estimating sleep, plots were made of the two raters Sleep/Wake designations. Figure 4 shows, for example, computer generated plots of the original scoring results from the same 10 records which were used in the reliability computations. Where the two lines (actigraph ratings atop EEG ratings) thicken, the subject was judged to be awake. Below each numbered pair of plots are indications of disagreemants. As can be seen, the actigraphic scoring judged sleep onset first 8 out of 10 times in these records. It is also of interest that subjects 1, 6, and 10 were three non-patients whereas the other 7 subjects were patients. As can be seen, the two methods for estimating sleep disagreed more often, on the average, in the case of patients, particularly subjects 3, 4, and 5. Subject 9 was an atypical patient whose record was more easily scored.

At a future date, we plan to investigate sources of disagreements by comparing plots such as those shown in Figure 4. These plots can be used to identify major scoring disagreements. We can then go back to the original records in order to closely examine the reasons for these disagreements. The computer plots can also be used to determine if a particular type disagreemant, for instance sleep onset time, occurs consistently.

Our present results for estimating TSP and TWMS in non-patients (r=.97 and r=.87) are comparable to our pilot results (N=5) where we obtained correlation coefficients of 0.95 and 0.85 respectively (Kripke, et al, 1978). Estimates of TST for non-patients produced a correlation coefficient of 0.95 in this study, slightly lower than the 0.98 correlation coefficient obtained in the pilot study.

In this study, we have demonstrated that the wrist actigraph is a reliable instrument for quantifying sleep time compared to standard EEG-EOG-EMG measures. Most investigators would probably assume that EEG scoring corresponds more accurately to behavioral and functional sleep than does actigraph scoring and, therefore, EEG scoring may be more accurate. While we have no objective comparisons of EEG and actigraphic scoring as indicators of behavioral sleep, our reliability data indicated that the agreement between EEG and actigraphic estimates of TST is only slightly less than agreement of two scorers rating the same EEG record. Therefore, the reliability of the wrist actigraph seems rather close to EEG reliability for quantifying behavioral and functional sleep.

In future studies employing actigraphic scoring to estimate sleep time it will be important to bear in mind the significant tendency of the actigraph to over-estimate TST. Even though the mean increase of 10 minutes is a small amount of time--only about 2% of a 7-hour sleep period-- the actigraphic over-estimation may be much greater with some individuals than others. One subject, for instance, fooled the actigraph scorer by waking up and then sitting still while meditating for the next 20 minutes before breakfast.

Although the two methods for estimating sleep employed in this study are comparable in terms of reliability, other factors such as simplicity of the actigraphic method and the expense of EEG recordings make the actigraph a more desireable method for many research and clinical purposes, studies of industrial health and clinical screening. Even if the EEG method is slightly more accurate in estimating sleep time, a cost-benefit analysis would often favor the actigraphic method for quantifying TST. Increased accuracy in a sample measurement is only valuable to the extent that the sample accurately represents the population from which it has been drawn.

Night to night and subject to subject variability in TST is so substantial that a small increase in accuracy is wasted. For example, among the 16 subjects for whom 2 nights were recorded, the night to night correlations for EEG TST were only r=0.392. The mean night to night standard deviation of EEG TST was 59.18. Thus, if we obtained, for example, 4 nights of recording for each subject, the mean standard error of the mean TST for each subject would be 29.09. On the other hand, the combined effect of night to night variability and method to method imprecision can be estimated by the standard deviation of EEG TST on one night compared to actigraphic TST on a second night. This standard deviation was 66.90. It will be seen, then, that the standard error of the mean actigraphic measures (including the error from the EEG estimate) would be 33.45 for 4 nights of recording. Let us further suppose that the cost of actigraphic recording were only 1/5th that of EEG recording (we believe it is actually closer to 1/10th that of EEG recording, and further cost reduction may be obtained with digital methods). Then, for an equal investment, we could obtain 20 nights of actigraphic recording leading to a standard error of the mean of 14.96. For an equal cost, then, the actigraphic method would be twice as precise as EEG for estimating mean TST. In addition, the actigraphic method produces less skin irritation and has a lower shock risk. The actigraph is more comfortable and convenient for the subject, who can sleep in his own bed if desired, free from electrodes. The adaptability of the actigraphic method to naturalistic settings also improves its accuracy as a measurement approach.

Thus, the actigraphic method of measuring sleep is a reliable method which actually allows more precise measurement of EEG TST than the EEG recording method for a given cost. It is also far more adaptable to naturalistic settings, particularly, to military settings. Nevertheless, we believe there is room for much greater improvement because the actigraphic method should be adaptable to computerization. We believe that an all-digital actigraphic recorder can be developed which will eliminate the need for the cassette tape recorder, and which will ultimately be adaptable to the wrist. A computer program can be developed to make scoring completely automated. Technologic development towards this goal, which should provide a still greater improvement in the cost-benefits of the method, will be the goal of our future contract work.

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GLOSSARY

EEG--Electroencephalogram

EMG--Electromyogram

EOG--Electroocculogram

MSA--Mid-Sleep Awakenings

Sleep Log--Subjective estimate of Sleep Time, SLeep Latency, and quality of sleep including the Stanford Sleepiness Scale.

Sleep Latency--Time to fall asleep measured from time of intent to sleep.

TSP--Total Sleep Period (span of time from sleep onset to end of sleep)

TST--Total Sleep Time

TWWS--Total Wake Time within the sleep period

REM--Rapid Eye Movement

FIG. 1
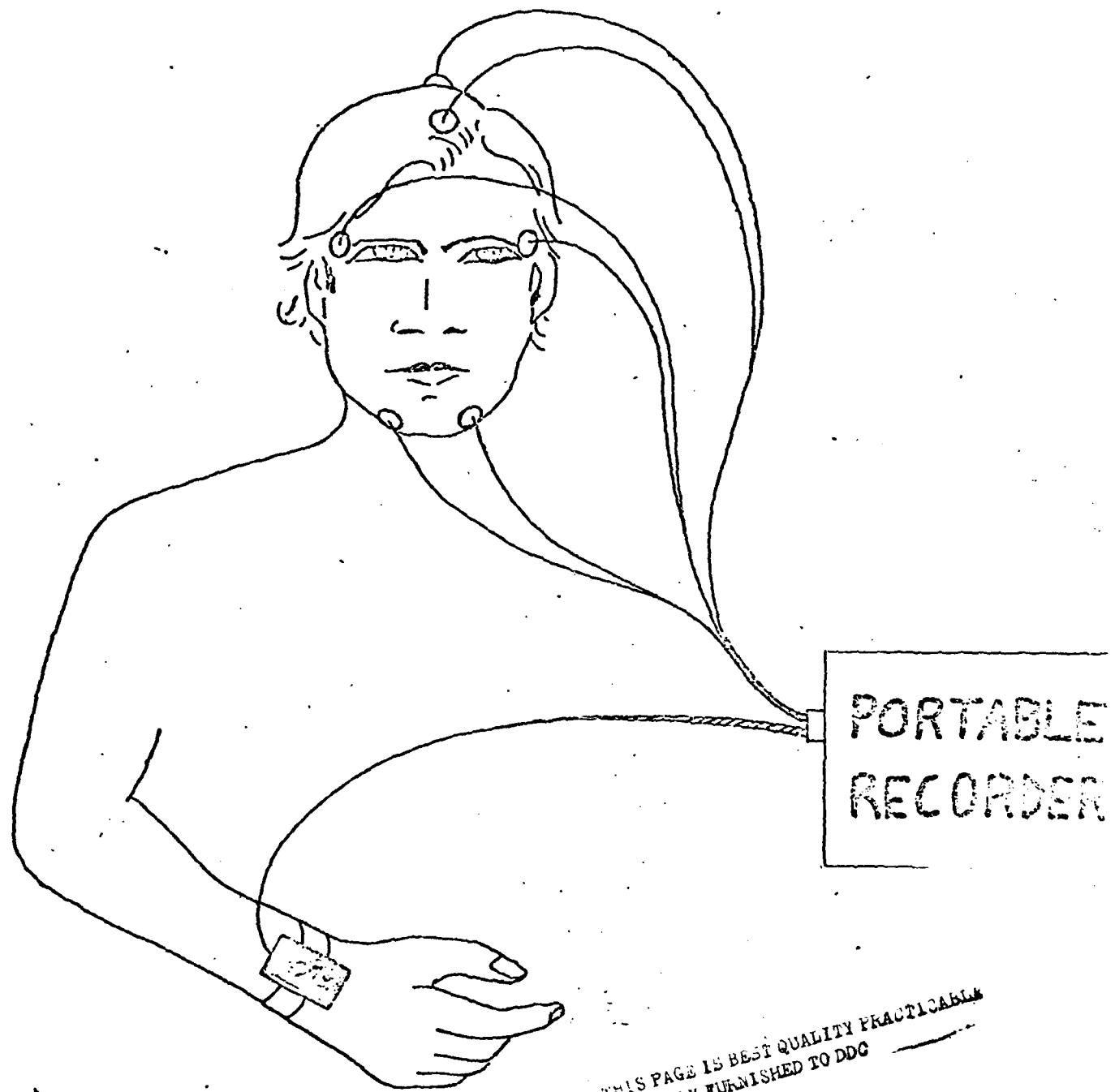
PORTABLE RECORDER

RECORD

SLEEP RECORD

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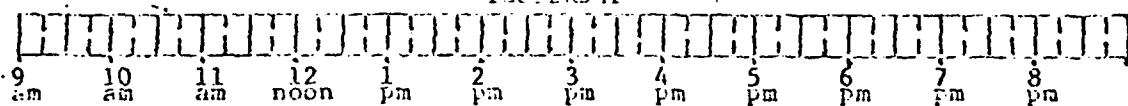
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DAY OF THE WEEK: _____
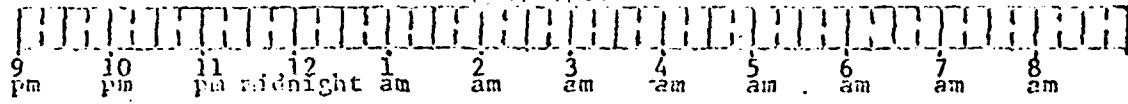
TIME FILLED OUT: _____

Please fill each box to indicate the hours you were asleep in the last 24 hours.
Mark each quarter hour. Do not blacken times during the night when you were
awake. Please mark all naps.

YESTERDAY

| 9 am | 10 am | 11 am | 12 noon | 1 pm | 2 pm | 3 pm | 4 pm | 5 pm | 6 pm | 7 pm | 8 pm |

LAST NIGHT

| 9 pm | 10 pm | 11 pm | 12 midnight | 1 am | 2 am | 3 am | 4 am | 5 am | 6 am | 7 am | 8 am |

How many minutes did it take to fall asleep last night? _____ min.

How many times did you awaken last night? _____ times

For how many minutes were you awake during the night? _____ min.

How long did you sleep last night? _____ hours and _____ min.

Did you awaken earlier in the morning than you wished? _____ yes _____ no

Do you feel you needed more sleep? _____ yes How much more? _____ hours
_____ no

How do you feel this morning?

_____ Feeling active and vital; alert; wide awake.

_____ Functioning at a high level, but not at peak; able to concentrate.

_____ Relaxed; awake, responsive, but not at full alertness.

_____ A little foggy; let down; not at a peak.

_____ Foggy; slowed down; beginning to lose interest in remaining awake.

_____ Sleepy; woozy; prefer to be lying down; fighting sleep.

_____ Almost in reverie; sleep onset soon; losing struggle to remain awake.

FIG. 2
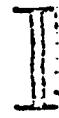
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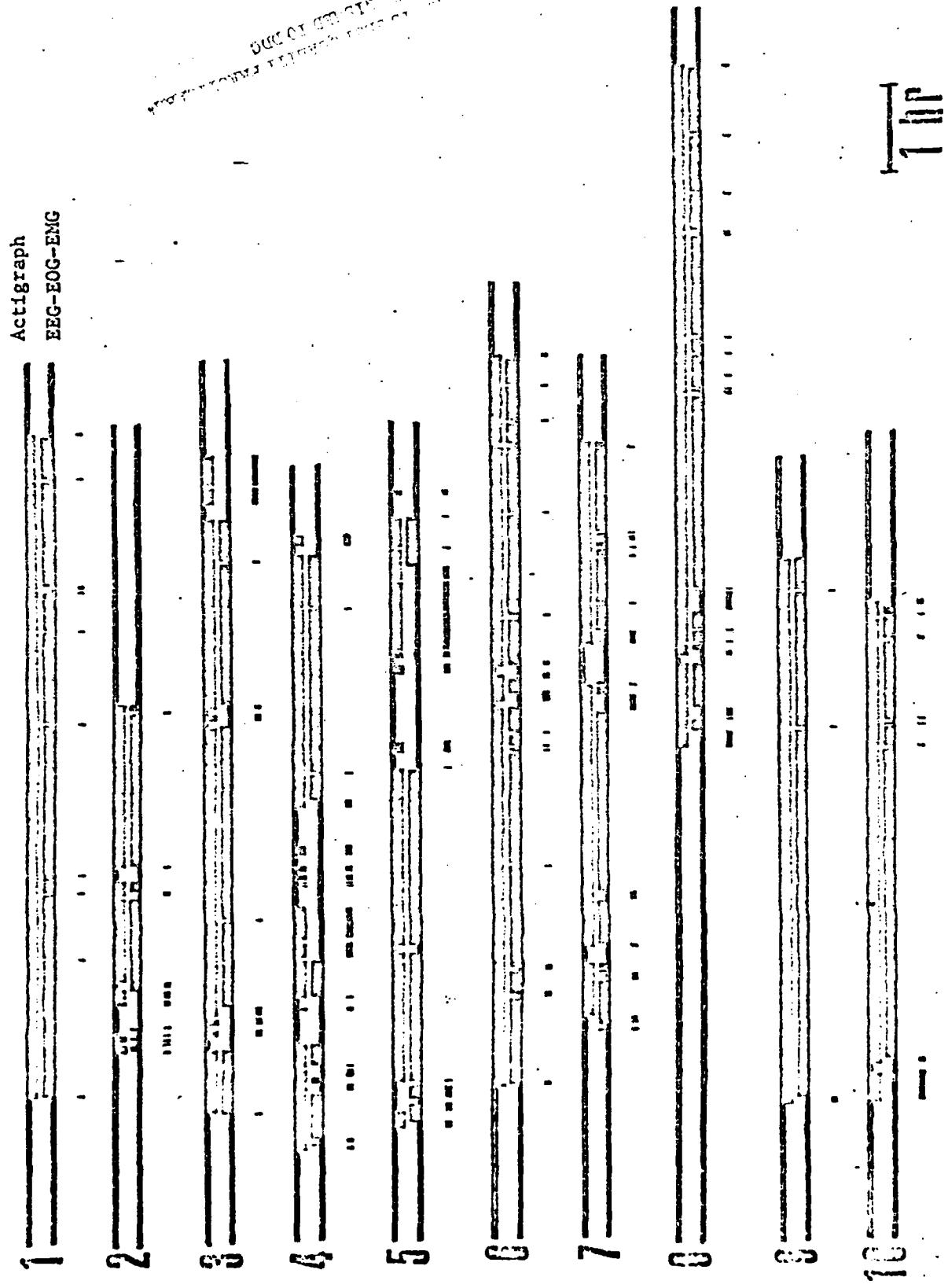
TABLE 1

CORRELATIONS BETWEEN ACTIGRAPHIC RECORDINGS AND EEG-EOG-EMG

METHODS FOR ESTIMATING SLEEP PARAMETERS (N=102)

SLEEP PARAMETER	r (ACTIGRAPH-EEG)	
Total Sleep Period	.90	(p<.0001)
Total Sleep Time	.89	(p<.0001)
Total Wake Within Sleep	.70	(p<.0001)
# Mid-Sleep Awakenings	.25	(p<.01)

TABLE 2

CTOR	TSP	TST	TWWS	#MSA
PATIENTHOOD				
PATIENTS (N=39)	.82*	.81*	.56*	.09ns
NON-PATIENTS (N=63)	.97*	.95*	.87*	.46*
	p<.0001	p<.001	p<.001	p<.05
AGE				
<50 (N=85)	.95*	.95*	.65*	.32**
≥50 (N=17)	.52*	.39ns	.82*	.01ns
	p<.0001	p<.0001	ns	ns
EEG TSP (minutes)				
<390 (N=36)	.74*	.78*	.66*	.52*
≥390 (N=66)	.85*	.83*	.72*	.19ns
	ns	ns	ns	ns
SLEEP LOG TST (minutes)				
<390 (N=49)	.79*	.69*	.70*	.23ns
≥390 (N=53)	.96*	.94*	.72*	.26****
	p<.0001	p<.0001	ns	ns
QUALITY				
HIGH (N=24)	.97*	.97*	.75*	.59***
LOW (N=20)	.78*	.79*	.74*	-.07ns
	p<.001	p<.001	ns	p<.05
INTERPRETATION				
HIGH (N=24)	.97*	.97*	.75*	.59***
LOW (N=27)	.77*	.83*	.62*	-.16ns
	p<.001	p<.01	ns	p<.01

Significance levels of correlation coefficients (one-tailed test)

*p .0001
**p .001
***p .01
****p .05

TABLE 3

RELIABILITY ESTIMATE

CORRELATIONS BETWEEN SCORERS AND BETWEEN METHODS (ACTIGRAPH vs EEG) FOR
ESTIMATING SLEEP PARAMETERS (N=10)

SLEEP PARAMETER	CORRELATION COEFFICIENTS		
	EEG-EEG	ACT-ACT	EEG-ACT
Total Sleep Period	.999 (p<.0001)	.981 (p<.0001)	.976 (p<.0001)
Total Sleep Time	.977 (p<.0001)	.979 (p<.0001)	.956 (p<.0001)
Total Wake Within Sleep	.968 (p<.0001)	.988 (p<.0001)	.964 (p<.0001)
# Mid-Sleep Awakenings	.899 (p<.0001)	.851 (p<.001)	-.079 (NS)

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